

# Recording augmented reality experiences to capture design reviews

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**Abstract** During design reviews, multiple stakeholders convene to reflect on the quality of intermediate results and to decide upon following steps. As prior research indicates, such design reviews are only partly a structured, rational process; often aspects as trust, hidden agendas or lacking commissioning skills influence this activity. Furthermore, a wide range of media is being used during these meetings, which are difficult to recollect in their context after the event. This research project attempts to improve design reviews in the domain of Industrial Design Engineering by two means: (1) by providing a specific prototyping and annotation device employing physical mockups, (2) by recording both communication between stakeholders and interaction with the prototype to produce comprehensive coverage of the review session. Based on literature and additional case studies, an analysis of the information streams is presented. Furthermore, an Interactive Augmented Prototyping solution is devised. Early verifications show that the recording resolution still requires a lot of fine-tuning, which will be the primary focus prior to a comprehensive evaluation in practice.

**Keywords** Augmented reality · Augmented prototyping · Design review · Recording · Industrial design

## 1 Introduction

In conducting a number of empirical field studies we found that collective decision making and discussions during design review meetings were essential in driving the design process. Even among the most pragmatic and functionalist thinking people miscommunication occurs, leading to sub-optimal designs, unnecessary delays and distrust. The recording and recollection of design review meetings is important; future decisions sometimes are based on the remembrance of prior meetings. Often, this administrative activity gets little attention or is over formalized to record specific events of the work but not its full discussion. Furthermore, meeting minutes can be biased, as they are made from the point of view of only one of the stakeholders.

As can be found in the field of Interactive Design [8], a vast collection of advanced prototyping techniques have emerged, including virtual and augmented solutions. Such techniques engage intricate simulation and multi-sensory interaction principles for improving decision-making in product design and manufacturing. However, the primary focus of this research domain is of a functionalist view—e.g. to simulate and validate product tests. We believe other, “softer” views should get more emphasis in order to become truly interactive prototyping means that has a positive influence on the overall design process [37].

In this article, we introduce a new prototyping concept, based on augmented reality technology. The presented I/O Pad is unique as it supports prototyping and recording in parallel. By employing this solution, physical prototypes are enriched with additional information (colour, features) that

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can be altered in situ, while all users can observe and interact when necessary. Based on extensive design case studies, we claim that these are well supporting the needs and requirements of stakeholders during design reviews in the field of industrial design.

This paper is structured as follows: first, literature is discussed covering design reviews, augmented prototyping, and related recording systems. Then, the proposed recording method is presented, which comprises both hardware and software concepts. Next, an initial system is presented to explore and validate the basic issues. The final section specifies the following steps in developing and evaluating this system.

## 2 Backgrounds

### 2.1 Interactive Augmented Prototyping

The concept of Interactive Augmented Prototyping (IAP) employs augmented (mixed) reality technologies to combine virtual and physical prototypes. Enabling technologies encompass display means, position sensing methods, interaction techniques, and physical model manufacturing. In particular, the display for augmentation ranges from video mixing and see-through displays to spatial augmented reality; in the latter case video projectors are used to cast computer imagery directly on physical objects [2]. Although projector-based display techniques have their limitations e.g. [12] it is easily accessible by most design studios. Human factors studies indicate that projector-based AR performs better than video-mixing head-mounted displays [23] and provides more object-presence than VR-based techniques as the virtual workbench [31]. Powerful interaction techniques can be shared in such systems. One of the first examples of this technique was presented by Underkoffler and Ishii [34], in which an urban planning scenario was followed. Physical wire frames represented blocks that could be placed arbitrarily on a plane. Real-time simulations were projected on the table, including reflections, shadows, and wind turbulence in its surroundings. Recent progress in this field allows sketching on arbitrary surfaces from various distances [4].

For the work presented in this paper, the projector-based AR display will be used to merge digital modelling and simulation with physical models, either made by hand or automatically by 3D printing or Rapid Prototyping processes. The main advantage of IAP techniques lies in its ability to provide natural haptic/tactile feedback and its mix with the physical environment. It constitutes an embodied interface, allowing natural spatial reasoning and supports social interaction in collaborative settings [6]. Compared to traditional physical prototyping techniques, possible advantages of Interactive

Augmented Prototyping are (1) the display of a new type of information (e.g. the wind simulation in the example above), (2) increasing the intensity of particular type of information (e.g. material expression by including texture maps), and (3) increasing the richness of interacting or the sense of engagement with the artefact representation.

### 2.2 Case studies in design

In order to obtain insight in the possibilities and limitations of current prototyping practice in industrial design, the authors have executed an empirically study of three design projects in different sub domains: the design of a tractor, a hand-held oscilloscope, and the interior for a museum [35]. Our objective was to produce a deep and accurate account of prototyping and modelling activities in a range of industrial design engineering domains, with a primary focus on product representation and design reviews. Although the design processes differed in many respects, common issues originated from mismatches between stakeholders, either because some design aspects are challenging to explicate (like aesthetics) or differences in values and attitudes.

From the case studies, it was quite apparent that design review meetings were one of the most influential constituents of the design process in which prototypes and other design representations are essential. In our forerunning theory forming, notions from Critical Systems Thinking are applied. According to this framework design review meetings and the employment of prototypes should be viewed from four separate paradigms, covering (1) the functionalist' stance, which focuses on utilitarian aspects such as the efficiency and quality of design results, (2) the interpretive, which is aimed at establish consensus and shared understanding, (3) the emancipatory, which considers power relations, e.g. how decision making and trust is influenced, and (4) the postmodernist, which attempts to cultivate an entertaining, pluralistic and creative atmosphere. Examples and issues concerning these were discussed in [37].

Based on the three case studies, a number of functions for Interactive Augmented Prototyping systems could be identified, categorized in four usage scenarios: user studies, exploration, design review and presentations to customers/higher management. The full collection includes over 29 functions. The ones that refer to design reviews are summarized in Table 1. In our case studies, the review sessions followed a structured agenda, often supported by a slideshow that presented solutions and design issues. In one of the case studies, the power of the narrative, storytelling was stressed; as a means to address abstract design aspects without resorting into concrete visual examples. Another important finding was the variety of roles a physical models play during a meeting with heterogeneous group of attendants., ranging from

**Table 1** Design review functions derived from three case studies

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Internal discussion of design alternatives, capturing interaction and reflections (annotation)
Freehand sketching on surface (captured with author+timestamp for later use)
Present user studies: usage feedback, co-located events and subjective evaluations
Presentation of design alternatives, capturing interaction and reflections and possibly design decisions (annotation)
Presentations of design exploration scenarios to support reasoning and try to convince client
Archiving and retrieving reviews (replay, overviews etc), allowing shared access
Ability to prepare the model for discussions, by fixing/filtering items and by setting a small number of configurations
Interactive display of colors/materials in focused areas only (similar to colored doll in existing model)
Combine physical model as an indexing tool for design details
To present usage scenarios (e.g. pedestrian flows)
Archival and retrieval of design reviews (replay, overviews etc), to be shared through network
Abilities to add coarse budgeting and design requirements tools with interior design
Present project status: design (alternatives), disciplines (design: industrial, interaction, engineering: electrical, mechanical, manufacturing)
Present a summary of most interesting user feedback
Present a variety of designs as a portfolio overview, either interactive or self running;
Present one particular product in its context and its specific (animated) features, kiosk mode

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objective design representations to create shared insight to selective constructs to defend decisions or to steer the meeting agenda.

### 2.3 Product design reviews

Instead of focusing on solitary activities of a single designer or engineer, research in engineering design has recently focused on collaborative aspects. However, the design review as an archetypical collaborative setting did not get much attention in literature. Mitchell [21] stresses that these reviews improve the design by establishing a unique event that combines information exchange, interaction, and conflict resolution. According to Turner [33] Design reviews represent a “formal documentation and interrogation instrument” in the design process. It focuses on assessing the intermediate design results by various criteria and a discussion on sub problems, in various ways of structured procedures [26,33]. Xijuan et al. [40] attempt to quantify the impact and effect of a specific design review by comparing the fidelity of the design before and after. However, each design review bears different discussions, timing and procedures.

As Perry and Sanderson [24] identified, a diverse range of design representations are employed during formal and informal design meetings, ranging from sketches and diagrams to documents, to physical models and digital data. Furthermore, additional sketches and annotations are generated during meetings. As the authors note, CAD software has little functionality to capture the full range of discussions during such meetings. This specifically extends to the verbal utterances and the references between the topics and to previous meetings/discussions.

In [13], an sequential case study of engineering design reviews resulted in two instruments to represent and visualize design review sessions, namely the information map and an meeting capture template. The first visually encodes the topics of a discussion and creates a network to show how these were inter-related. The meeting capture template is a tabular scheme to record topics, decisions and actions. This format proved to be useful in the studies, and should be considered in developing new design review support tools.

### 2.4 Related systems

Commercial modelling packages offer 3D design review systems, for example Autodesk’s Design Review which can be used without cost. These enable loading a set of CAD entities and to inspect and annotate (pen and text) the 2D and 3D models [1]. For example, Autodesk’s Design Review does support simple overlay sketching, but is not suited to capture the know-why behind these symbols by voice/video recording. In general, these systems are meant for single-user use, and have limited capabilities to capture multimedia.

Both Kremer [16] and Knopfle and Voss [15] propose a VR-based system that allows users to inspect models by showing and hiding parts, obtaining dimensions and a simplistic means to add text comments. Although the article specifically targets design reviews, little support is provided to prepare, execute or document such meetings. Similarly, [22] and [30] both employ optical see-through Head Mounted Displays to inspect designs, but little support is provided to the act of reviewing. The ability to annotate 3D models is for example presented in [14], who discern simple text comments (similar to post-it notes) from sketches in 3D. The

IMPROVE project explicitly addresses design reviews for product design, its main focus lies with hardware and algorithms for photo-realistic rendering, the annotation facility is minimal [29].

A comprehensive design review solution based on VR was presented in [32]. The authors employ a LCD touch panel on a moveable kinematical structure called Boom Chameleon to act as a physical window to a virtual scene. The system supports so-called spatially embedded snapshots, which show a design from a specific viewpoint. These hover around the 3D model of the design in question and can be used to annotate as a 2D overlay established by the touch panel. Furthermore, the system employs a “flashlight” tool to draw directly on the 3D surfaces. However, viewing and inspecting artefact models is limited to a single user. Furthermore, no physical model can be employed to collaboratively address details or inspect the design by tactile senses and experience it in the intended scale. Finally, no record is made of remaining aspects of the design review meeting, e.g. verbal communication.

A similar shortcoming prevails to Augmented Reality systems. None allow recording facilities, although there are a number of story-writing systems, which support on playing narrative experiences in AR systems by scripting and arranging interactive components, such as DART [19], Geist [17], and the APRIL language [18]. Greenhalg et al. [10] propose to support capturing all virtual events in a VR system and offer a virtual playback facility called Holovid—a miniature version of the virtual world accessible by all virtual partners. However, this system is not equipped to record video or audio.

In the field of computer supported cooperative work (CSCW), multimedia technologies were already employed to structure and merge different data streams. For example, Potts et al. [25] attempted to capture a brainstorming meeting in which the note-taker uses a computer-based hypertext editor. The user-input events are treated as segmentation indices for a computer-controlled video tape recorder (VCR). By clicking on hypertext nodes, the appropriate video sequences are played, recollecting the discussions that happened when the specific digital object was created and modified. The “Where Were We” system was developed for similar purposes, enabling the use of multiple digital whiteboards and digital video recordings, to be instantly accessible [20]. This system architecture explicitly identifies a “event index”, which is a shareable database of events which steer the video capturing and playback. What was unique in the Where Were We system is that its proposed use was both recording and revisiting multimedia streams at the same time. This did sometimes lead to a confusing experience by rapidly shifting from active discussion to reviewing the session.

The Round Table system from Microsoft [5] supports spatialization and identification of speakers based on location of

the sound, which could be added to prospective recordings systems.

In the domain of usability engineering, a collection of interaction multimedia recording techniques have been devised to capture user experiences of products. For example, the d.tools system is able to connect physical mock-ups to a PC, which in turn simulates system behaviour and monitors user interaction [11]. The user is recorded by multiple media (video, audio, application state) and the resulting recordings can be accessed later by controlling a interaction diagram. A similar approach of capturing and charting product interaction will be used in our system, extended by the semantics of design review.

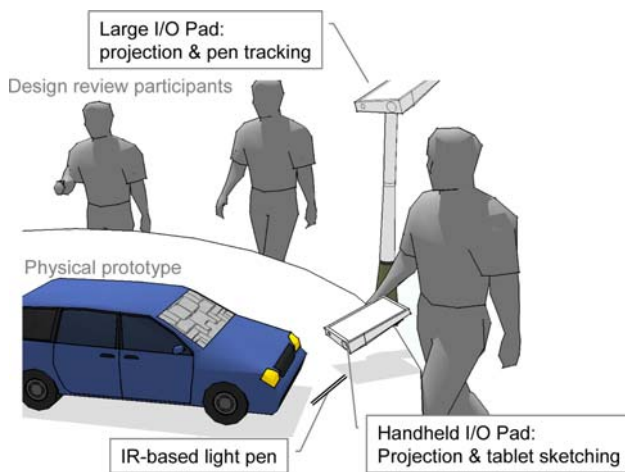
### 3 Proposed Augmented Prototyping and recording method

#### 3.1 Hardware: the I/O Pad platform

To establish augmented reality for design, a growing selection of output, input, and physical prototyping has to be considered. A treatise of these enabling hardware technologies was published in [36]; as output means, our first preference is the projector-based display. On input and physical model making, a wide variety of options is available, none of which provided a complete solution.

As a fundament for the hardware platform, we would like to adopt the paradigm of the I/O bulb as presented by Underkoffler and Ishii [34]. The I/O bulb (Input-Output bulb) views the input (camera or other sensors) and output (projector) as one single unit. This bulb can be switched on and off at will, can be configured in groups and so on. For example, each I/O bulb could perform a particular task: 3D modelling, simulation analysis or annotation management. In this fashion, dedicated projector modules can be viewed as a physically addressable (i.e. tangible) component. As demonstrated by the so-called procams community (projector-camera systems), many algorithms and applications have evolved that can be employed in this set-up including calibration of colour temperature, 3D scanning, and visual echo-cancelling. We extend the I/O bulb concept, by including processing power and a touch screen interface, the result of which we would like to label as I/O Pad. As its name suggests, it is supposed to fit within the series of tangible user interfaces devised to blend physical and virtual realms like I/O bulb and I/O brush [28].

The I/O Pad is a self-sufficient, untethered device. Collaboration of multiple pads is facilitated through wired or wireless network connections. Its operation during design reviews is shown in Fig. 1. Different instantiations of the I/O Pads might be used concurrently, e.g. to provide global illumination by a distant system and to interact with detailed features



**Fig. 1** Impression of both I/O pads during a design review

by one I/O Pad close to the physical model. According to the user's wishes, some pads might be switched on or off or moved during sessions.

I/O Pads can be small and portable, or they carry increased projection and computing power. Two extreme versions have been conceptualised, as specified in Table 2. For a handheld system, a small LED-based projector is appropriate; which runs on batteries and is almost silent. As a processing unit, an Ultra-Mobile PC (UMPC) is a good candidate; it contains a touch screen and in fact is a miniaturized PC that runs standard windows or Linux software. Due to the lack of computing power, a lightweight 3D tracking system should be selected, for example ARToolkit. This is an open source library for optical 3D tracking and tag identification that employs flat rectangular markers [KB1]; our field tests suggest it will perform well on the UMPC platform (approximately 20 Hz,  $640 \times 480$  camera resolution).

The larger I/O Pad is equipped with more powerful constituents, to offer improved projection, processing, and 3D tracking. Recent video projectors offer XGA or higher resolutions and produce over 3000 Lumen. As processing and

interaction unit, we propose the employment of a high-end Tablet-PC with a touch screen option. Such Tablets harbour both active and passive touch technologies and can be operated by fingers and special pens. In the latter case, the tablet is pressure sensitive, which supports the natural expressiveness of designer's sketching abilities. To support 3D tracking and user events, this system can be equipped with an infrared camera and infrared lamp, as being found in typical motion capture systems like Motion Analysis and Vicon. By deploying retro-reflective passive markers in combination with active, LED-based tags, both fine-grained 3D component tracking and user interaction with physical components (by for example phidgets) will be supported. This I/O pad is meant to offer global lighting of a design/environment, from a larger distance. Due to its weight, proper fixture like a professional tripod is essential.

In essence, our concept overlaps with iLamps [27]; both add handheld, geometrically aware projection and allow ad-hoc clustered projections. However, the I/O Pad differs in three ways: (i) each I/O Pad contains a touch screen to interactively capture and display sketches and gestures from designers, (ii) each pad is equipped with recording devices (webcam) to pick up discussions and usability assessment sessions, and (iii) the I/O Pad network architecture encompasses a distributed structure to facilitate data sharing, dialogue management and in particular session recording,

The pilot implementations of these two I/O Pads, see Fig. 2, contain the following equipment. The smallest contains a LED-Based projector from Toshiba (FF-1), which weights 750 grams including battery. This projector is connected to an Asus R2H UMPC (900 MHz ULV Celeron processor, 500 MB RAM), which has a 7-inch passive touch screen. A Microsoft NX-6000 web camera delivers up to 2 Mega pixel resolution video images. This package weighs approximately 1,5 kilograms in total. The larger I/O Pad is based on a standard video projector (Epson EMP-811) that has 2000 lumen and is capable to project at XGA resolution ( $1,024 \times 768$  pixels). A Tablet PC delivers processing and a passive touch screen (HP TX1000, AMD dual-core

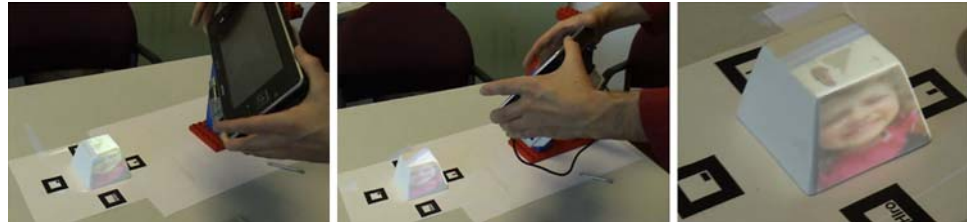
**Table 2** Characteristics of smallest and largest I/O Pads

	Handheld I/O Pad	Large I/O Pad
Projector	LED-based, battery operated	Silent standard video projector
Projector power	30 Lumen	3,000 Lumen
Projected resolution	$800 \times 600$ pixels	$1,280 \times 768$ pixels
Working distance from object	10–50 cm	100–300 cm
Processing unit	UMPC	Tablet PC
Touchscreen diameter	5–7 Inches	12–15 in.
3D tracking	Optical fiducial-based (ARToolkit)	Active/passive infrared tracking (motion capture system)
Estimate total weight	1 kg	2.5–3 kg

**Fig. 2** I/O Pad pilots of handheld (*left*) and large (*right*)



**Fig. 3** Interactive projection by the handheld I/O pad



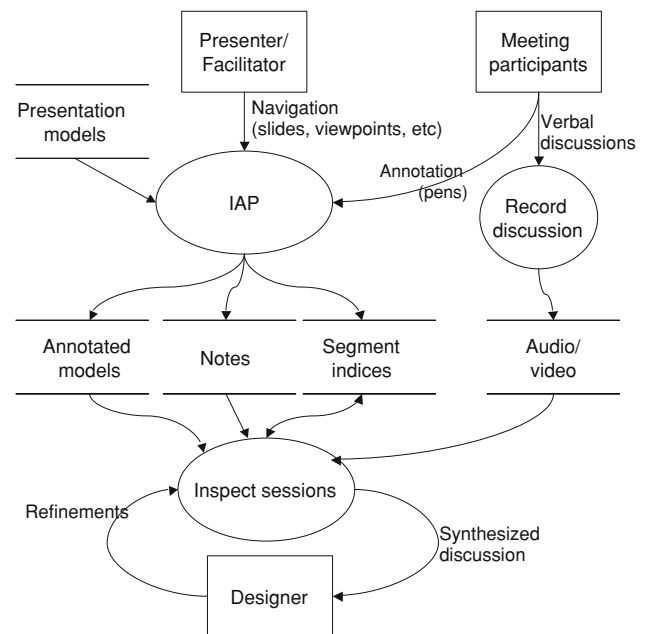
TL50 processor, 1GB RAM, 12,1-inch screen). For Infrared motion capturing the system currently employs a Wii remote controller (also known as WiiMote), which is able to track 4 points simultaneously at a resolution of  $1,024 \times 768$  pixels at 100Hz. This WiiMote game controller is connected wirelessly through Bluetooth. This complete bundle weighs approximately 2.5 kg and requires a professional tripod to aim at the area of interest.

Figure 3 shows the handheld I/O Pad in action. Four standard ARToolkit markers were placed around a simple object (a cup resembling a cropped pyramid). In this particular case, the geometry was modelled in Catia and texture maps containing arbitrary pictures and drawings were added to its faces. The user interaction is performed by either operating the touchscreen (finger or pen), moving the model, or writing on the physical scene with an infrared lightpen. The position of the lightpens is captured by the WiiMote controller; each lightpen emits pulses at different frequencies, enabling identification of the pen and user who controls it.

### 3.2 Design review functions

Our initial concept of the IAP Design Review system has been devised to support synchronous, co-located meetings that typically do not employ advanced recording techniques. The functions and related dataflow of the design review system is depicted in Fig. 4.

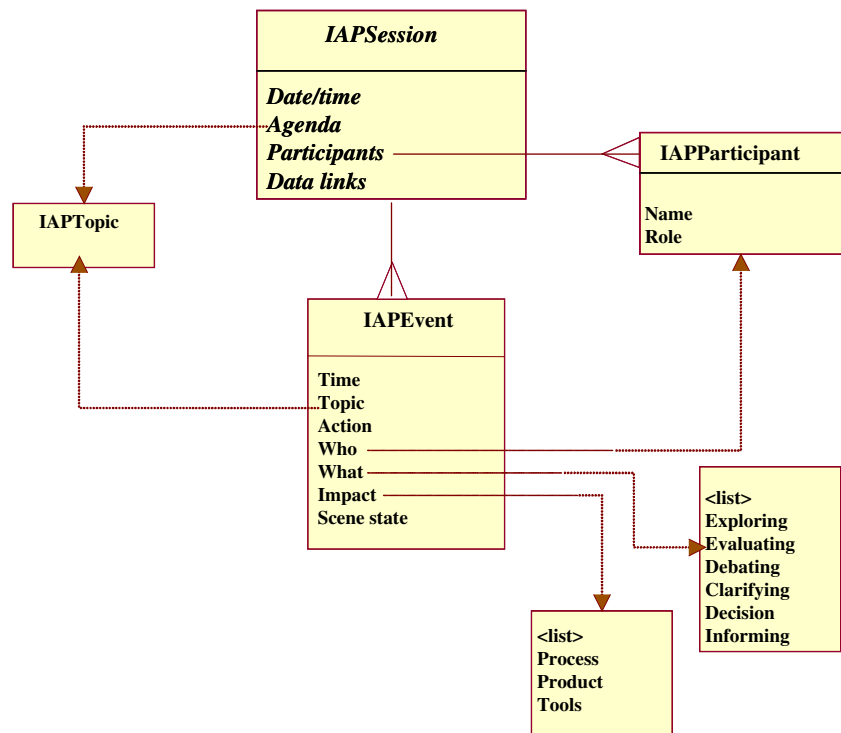
It supports three activities: (1) preparing the design review by arranging presentation models and sequence, (2) executing a design review, and (3) inspect and refine previously recorded meetings. The preparation is done by the design team, and will incorporate several presentation means, including slideshows, drawings, models and the like. After



**Fig. 4** Data flow of IAP Design Review system

setting up the hardware, the IAP Design Review system is started to perform calibration (see next section) and start the presentation. During the presentation, video of both I/O Pads is captured by the recording process, while interaction with the pens and navigation through the presentation are recorded as notes; input events are stored as well in the segment index, similar to the Where Were We system [20]. Inspection of sessions is available through a session browser, it presents meetings as timeline, all notes and annotations can be viewed in context of a 3D scene or the 2D presentation slide.

**Fig. 5** Representation scheme for design review sessions



### 3.3 Representation

The system is focused on capturing various aspects of design review sessions, the storage of the session will be based on a XML-based format. Based on the meeting capture template described in Huet et al. [13], a representation scheme was developed as shown in Fig. 5. The first-class objects are IAPSession and IAPEvent. The first describes the meta-data of a review session, referring to an agenda, participants and other data (such as the materials used and links to external video and 3D scenes). The agenda topics need to be defined on beforehand (stored in a XML list structure), and the I/O Pad will support navigation between the topics by dedicated keys. The IAPEvent object represents either manual or automatically generated meeting items that bear importance to the session. These might be user interface actions such as topic navigation, pen strokes or the selection of different design alternatives, or post-session notes. An IAPEvent instance consists of a universal timestamp, a reference to the current state of the 3D scene, and a number of fields that are compatible with the meeting capture template [13]; The topic refers to one of the IAPSession's agenda items. The action field refers to a predefined list (exploring, evaluating etc) The current user is recorded in the who-field, although recognition of the participants is only possible for pen events, others need human intervention. Specific action information is stored in a string field called what—which might include automatically generated data such as pen strokes or user

comments. Finally, the impact attempts to demarcate the action focus by identifying process, product, or tools.

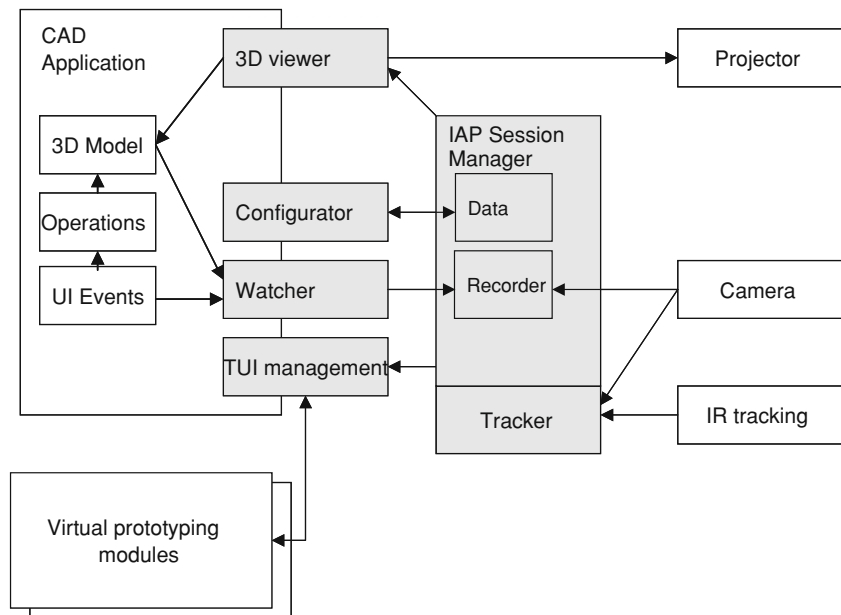
### 3.4 Software Architecture

The Software Architecture developed by the authors for the I/O is Pads coined WARP 2.0 [38]. It is based on a plug-in architecture and can be suited to a number of off-the-shelf CAD packages. The main framework is depicted in Fig. 6. In the centre, the IAP Session Manager is shown. It is responsible for setting up sessions at one or more I/O Pad. This includes model sharing, session recording, and configuration management. The recording function will combine the modelling history with discussion by recording video and audio as well.

On the right, the set of input and output devices are shown. Processing of input signals and 3D tracking is performed by a Tracker subsystem, which supports a large number of commercial and research position sensing devices. It is based on a data flow paradigm, enabling flexible combinations and conversions of data streams (even sharing though networks) that are defined in a XML format. The data flow based paradigm also enables easy recording of movement and configurations by storing the streams to persistent memory.

Key constituent of the IAP architecture is a third-party 3D modeller or simulation package, depicted on the left. Instead of creating our proprietary visualization solution, we intent to exploit the fact that most designers already use some

**Fig. 6** WARP 2.0 Software Architecture for Interactive Augmented Prototyping



3D modelling package like Catia, Solidworks or Rhinoceros. Most of these are capable render the virtual components in real-time, adjusted for the projector by means of configuring and maintaining a virtual camera. Furthermore, most modeling packages can be extended by scripting, macros or other automation mechanisms (like ActiveX). For supporting IAP, we have defined four plug-ins that need to be implemented for a particular package: (1) Configurator, (2) 3D Viewer, (3) TUI Management, and (4) Watcher. The responsibilities of these are discussed below.

The Configurator plug-in can be viewed as the local liaison of the IAP session manager—it is responsible for the local setup and execution of other plug-ins, loading/saving models and sharing this with other IAP instances. Furthermore, it offers an auto-start function and a GUI to arrange the IAP in line with the defined application scenarios and the related functions.

The 3D Viewer is responsible to define and update a virtual camera that copies the internal and external parameters of the attached projector. Internal parameters include field of view, aspect ratio and projection center; external parameters correspond to translation/rotation of the projector and the scale of the virtual and real-world coordinate systems. In terms of 3D computer graphics concepts, these are being specified in two transformation matrices: a projection and model matrix [9]. In some cases, these transforms need to be mapped to different units for the CAD package (e.g. CATIA requires focal point instead of field of view). When the I/O pad is moved, the virtual camera will have to update the model transform accordingly, based on the input from the IAP session manager. Ideally, the 3D viewer plug-in should sense alterations in projector zoom (focal point) and adjust the projection

matrix accordingly. Furthermore, the 3D Viewer module is responsible for determining the appropriate field-of-depth and should be capable to adjust the focus of the projector when required (based on distance between the projector and objects in virtual space).

The motion capture system will track individual physical elements including identification, position and possibly state (e.g. button press). The TUI-management plug-in is in charge of mapping these actions to the corresponding virtual components in the modelling or simulation package. This might effect in showing/hiding and translating/rotating objects but also steering additional simple modelling or annotation and virtual simulation modules (like physics behaviour or screen navigation).

Finally, the Watcher plug-in is responsible to support the recording functions, which can be either saved to file or streamed to a centralized session recorder through a network connection. This plug-in offers a number of services, including capturing either screenshots, full 3D models per stage, or hybrid version of both based the modelling events the hybrid option could for example encompass capturing full 3D models after alterations of the model, and screenshots during model viewing. Furthermore, the update frequency can be set in time or event-based triggers.

In order to enable concurrent use of multiple I/O Pads, a networked system layout is necessary. An overview of a typical setup is shown in Table 2. As a main communications solution, we have selected OpenSound Control protocol [39], which is currently supported by emerging tangible user interface development kits. For each projector unit, a single application instance should run with its corresponding plug-ins.



### 3.5 Calibration

Based on prior research, for example documented in [2], we developed a three-stage procedure to calibrate the projection. During the second and third stages, the projector is required to be fixed relatively to a special calibration object (we built a small fixture for this purpose).

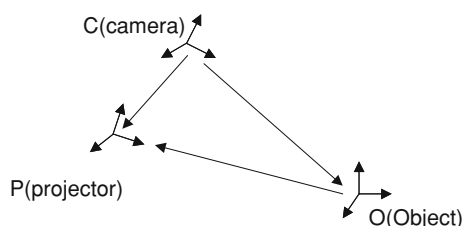
For employing an optical tracking technology, the camera needs to be calibrated first. Most systems such as ARToolkit are equipped with predefined methods and applications to support this. For standard cameras this action can be omitted, as calibration files are already provided. In general this calibration is only required once as the camera's internal parameters will not be changed.

The second stage deals with extracting the internal and external parameters of the projector, relative to a simple calibration object. By considering a projector as a dual of a camera, it employs Faugeras' Linear Camera Calibration algorithm from [7, p. 55 and further], See the Appendix for a summary of this algorithm. To establish this, the user is requested to specify the projected locations ( $u, v$  coordinates) for each of the eight vertices of the physical object ( $x, y, z$  coordinates). This is done by operating the touch screen. The result is processed in a system of equations, to map each ( $u, v$ ) with corresponding ( $x, y, z$ ) coordinates. A solution is calculated by applying the least squares method of the resulting equation. Subsequently, both projection matrix and model matrix can be separated from this data. In theory, this calibration step only has to be performed once for a fixed focal distance of the projector—the LED-based projector has no zooming options.

The final stage considers the geometrical transformation between camera and projector, depicted in Fig. 7. This is done by linking the ARToolkit coordinate of the object, the transformation  $C \rightarrow O$ , with the model matrix of the projector  $P \rightarrow O$ , determined in the previous stage. The transformation between camera and Projector can then be determined by:

$$C \rightarrow P = C \rightarrow O \cdot (P \rightarrow O)^{-1} \quad (1)$$

This last calibration has to be done once as well, although we have experienced several times that the camera was slightly moved with respect to the projector:



**Fig. 7** Relations between coordinate systems of the I/O Pad

### 4 Initial application

We are currently building both hardware and software platforms. The calibration procedure was developed and tuned for the simple object as discussed in Sect. 3.5. We have built a pilot plug-in set for Catia with limited functionality, allowing only rotation among 1 axis. It was employed to project on a CNC milled model of a racing car concept. To further investigate the recording functions, we have implemented a stand-alone OpenGL-based geometry viewer, which imports several VRML files and renders these according to multiple-marker configuration in ARToolkit. In particular, the test application renders four different sets of bitmaps on top of the cropped pyramid. Joystick keys on the UMPC are used to navigate between the different collections (left and right). The “OK” button is linked to a “Decision” event, which does not alter the state of the application but is logged this for later use.

To replay the recorded sessions was, an initial movie playback system was made as shown in Fig. 8. The application reads the session data from file, displays a timeline with bookmarks corresponding to the IAPEvents (shown in brackets). The application supports simultaneous playback of video and audio sequences. In the example session three events were logged, corresponding to the joystick operation described above (next model, previous model, decision). Two video windows are located the centre; the left view corresponds to the camera view from handheld system, the right to the view of the fixed I/O Pad. When a bookmark on the timeline is clicked, the videos and the timeline indicator will start playing from that corresponding point in time.

The computing power of the UMPC proves to be sufficient to support ARToolkit tracking and rendering in full speed. Although the resulting pilot's hardware is a bit bulky and heavy to lift for longer periods of time, the system can be easily transported, installed, and moved while running the software. As far as recording is concerned, some initial tests indicated performance penalties when accessing the OpenGL pipeline on the UMPC system—slowing down the frame rate to 8–10 Hz. This either has to do with intensive disk access for storing video or the single-threaded nature of the existing application which blocks the tracking-visualization loop at each frame. Apart from implementing a multi-threaded solution, it might be worthwhile to employ an external application to capture the screen, possibly employing a server-based solution like vnc to stream and combine the audiovisual channels.

To decrease the processing burden of recording and the resulting file size, the resolution of the video coverage (size and update frequency) might be constantly adapted. The level of detail of recording can be based on: camera/object movements, level of the microphone, and input events that influence the changes in the model. We will investigate such aspects in the forerunning study.

**Fig. 8** Initial playback application of recorded sessions



Another challenge ahead is the access and navigation through these reviews. Although sessions can be replayed in a chronological order (video streams plus modelling events), it makes more sense to offer other interface techniques that are catered for clustered data management. The playback application described above acts as an initial test. We would like to support a tabular editing environment to add new events and to filter those events that are important. The ShowMotion Technique might be interesting to adopt [3]. This technique offers navigating through “temporal thumbnails”, which are moving 3D cuts based on cinematic visual transitions. Such a set of animated parts of the design could enrich the inspection and comparison of several versions of a design.

## 5 Conclusions and future work

Design reviews play an important role in the design process. Such meetings between different stakeholders in intermediate stages of the design process require appropriate tools and methods to cover discussions, in obtaining shared understanding, in decision-making and in appreciating the work and its outcome. Specifically, facilities to prepare, annotate, and record design review play a crucial role in identifying and recollecting concerns. The presented I/O Pad is unique as it supports prototyping and recording in parallel.

By employing the presented augmented prototyping technologies, recording facilities can combine audio, video, model changes, and user annotations. This results in a large, data warehouse of multimedia indexed by semantic tags (decisions, tool usage, camera switching and the like). To our knowledge, this endeavour is the first to capture experiences by recording all channels of augmented reality sessions.

At present, the support scenario is aimed at co-located synchronous design reviews. A collection of systems can be used by multiple users to prototype and annotate simultaneously. Other uses, such as dislocated or asynchronous use will be investigated later.

Based on the I/O Pad hardware we have established an initial implementation of the concepts. The approach is far from complete, requiring a lot of attention to the resolution and the dissemination and indexing of the recorded sessions. Despite these issues, our impression is that the initial application demonstrates a useful addition to traditional design reviews.

In the near future, the technical platform will be extended and then field studies will be conducted to evaluate the resulting system in a number of design domains within industrial design engineering.

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## Appendix: Linear camera calculation

This procedure has been published in [7] to some degree, but is slightly adapted to be more accessible for those with less knowledge of the field of image processing. C source code that implements this mathematical procedure can be found in Appendix A1 of [2]. It basically uses point correspondences between original  $x, y, z$  coordinates and their projected  $u, v$ , counterparts to resolve internal and external camera parameters. In general cases, 6 point correspondences are sufficient [7, Proposition 3.11].

Let  $I$  and  $E$  be the internal and external parameters of the projector, respectively. Then a point  $P$  in 3D-space is transformed to:

$$p = [I \cdot E] \cdot P \quad (2)$$

where  $p$  is a point in the projector's coordinate system. If we decompose rotation and translation components in this matrix transformation we obtain:

$$p = [R \cdot t] \cdot P \quad (3)$$

In which  $R$  is a  $3 \times 3$  matrix corresponding to the rotational components of the transformation and  $t$  the  $3 \times 1$  translation vector. Then, we split the rotation columns in to row vectors  $R_1$ ,  $R_2$ , and  $R_3$  of formula 3. Applying the perspective division results in the following two formulae:

$$u_i = \frac{R_1 \cdot P_i + t_x}{R_3 \cdot P_i + t_z} \quad (4)$$

$$v_i = \frac{R_2 \cdot P_i + t_y}{R_3 \cdot P_i + t_z} \quad (5)$$

in which the 2D point  $p_i$  is split into  $(u_i, v_i)$ . Given  $n$  measured point–point correspondences  $(p_i; P_i)$ ;  $(i = 1 :: n)$ , we obtain  $2n$  equations:

$$R_1 \cdot P_i - u_i \cdot R_3 \cdot P_i + t_x - u_i \cdot t_z = 0 \quad (6)$$

$$R_2 \cdot P_i - v_i \cdot R_3 \cdot P_i + t_y - v_i \cdot t_z = 0 \quad (7)$$

We can rewrite these  $2n$  equations as a matrix multiplication with a vector of  $12$  unknown variables, comprising the original transformation components  $R$  and  $t$  of formula 3. Due to measurement errors, a solution is usually non-singular; we wish to estimate this transformation with a minimal estimation deviation. In the algorithm presented at [2], the minimax theorem is used to extract these based on determining the singular values. In a straightforward matter, internal and external transformations  $I$  and  $E$  of formula 1 can be extracted from the resulting transformation.

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